Journal of Electrostatics 71 (2013) 673–680

Contents lists available at SciVerse ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Review

Numerical models in simulating wire-plate electrostatic precipitators: A review

K. Adamiak

Department of Electrical Engineering, University of Western Ontario, London, Ontario, Canada

ARTICLE INFO

Article history:
Received 5 November 2012
Accepted 3 March 2013
Available online 19 March 2013

Keywords:
Electrostatic precipitation
Electrohydrodynamics
Numerical simulation
Particle transport and deposition
Ionized electric fields
Turbulent flows

ABSTRACT

This paper attempts to review the most important works on numerical simulation of processes in electrostatic precipitators published so far. Only the wire-plate configuration is considered, although the discharge electrode may have different geometries: smooth cylinder, barbed wire of different shape or helical electrode. Different mathematical models and numerical algorithms for gas flow, electric field, corona discharge and particle transport have been compared. The discussion is focused on coupling between different phenomena. A continuous progress has been shown from early works published about 30 years ago, which dealt with much idealized models of the problem, to recent publications, where the numerical predictions show close agreement with the experimental data.

1. Introduction

It is difficult to believe that the first idea related to electrostatic precipitation (ESP) was discovered more than 400 years ago – in early 1600's Gilbert has noticed smoke attraction to electrified bodies [1]. The first electrohydrodynamic experiment, demonstrating the so-called ionic wind, was performed 303 years ago by Hauksbee [2]. At that time, this was just a curiosity and for long time nobody even believed it will ever have any practical significance. The principle of particle removal by their electrical charging and exposing to an external electric field was demonstrated 189 years ago [3] and the first commercial invention was patented in 1884 [1]. In 1925 Deutch connected both ideas and showed the influence of ionic wind on electrostatic precipitation [4].

Considering this long history, it is surprising that ESP still attracts interests of engineers and researchers. The fact is that it is relatively easy to collect large particles, for example, larger than 1 μm, if they are not too resistive. The transport of such particles is dominated by electric forces, their collection efficiency is very high and details of the flow pattern and ionic wind are not really so critical. Collection of very small, submicron, particles is much more difficult and many of them usually escape from the conventional devices. The new environmental regulations pay more and more attention to these particles, as they can be potentially hazardous for human health. Therefore, many different research teams are looking for new ways to improve this process. However, designing a new kind of precipitator is not possible without detailed understanding of all phenomena affecting the process.

It is well known that there are three basic phenomena taking place in any ESP: gas flow, ionized electric field and particle transport (Fig. 1). All of them are mutually coupled, although some couplings are weaker than others and can be neglected. It is commonly accepted that while the EHD flow generated due to corona discharge may have a relatively strong influence on the flow pattern, the reverse coupling (charge convection) is much weaker. This is obviously true in the area close to the corona wire: electric field is strong there, so the ion velocity is much higher than the gas velocity and the charge convection can be neglected. However, in the precipitation channel there are also some areas relatively remote from the corona electrode and close to the ground plate, where the electric field is much weaker and the ion drift velocity can be comparable with the gas velocity. Nobody has yet verified if this has any effect on the particle collection. Another coupling, which is usually neglected in the precipitation model, is the particle-gas coupling. Mechanical coupling between particles and gas for small particle concentrations can be neglected without causing substantial errors. However, there is an indirect coupling: particles are charged, so they form a space charge. This charge interacts with the electric field and body force is generated, which affects the flow pattern.

Experimental investigation of such complicated systems is very expensive, so there is a natural idea to simulate the process

E-mail address: kadamiak@eng.uwo.ca.

0304-3886/$ – see front matter
http://dx.doi.org/10.1016/j.elstat.2013.03.001

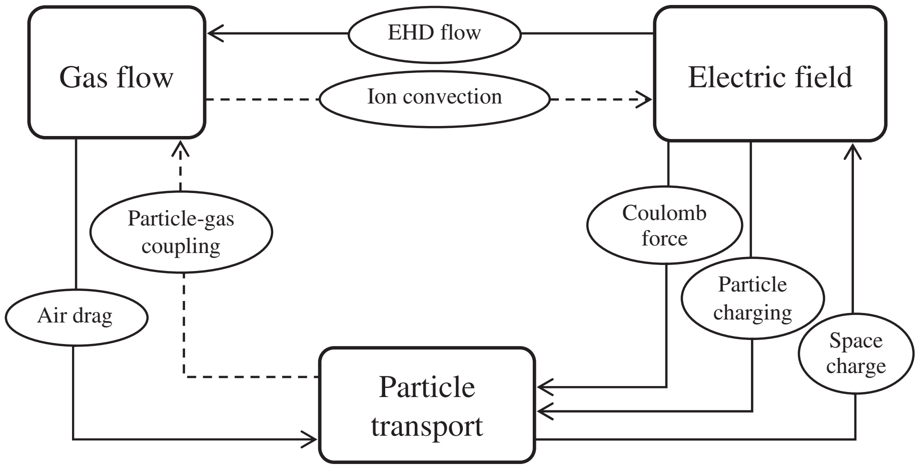

Fig. 1. Mutual coupling between different phenomena in electrostatic precipitation.

numerically. However, due to enormous complexity of the problem, a full numerical model is still impossible and many simplifications are necessary in order to keep computational costs at a reasonable level.

Different authors have used various idealizations of the process trying to simulate the process using available computing equipment in reasonable time. An impressive progress in the speed and capacity of the computing equipment can be observed during the last 20 years or so. In this situation, there is also a dramatic improvement in the size of considered models and accuracy of calculations. The paper attempts to review the most important works on numerical simulation of ESP from earlier works in this area until the most recent publications.

2. Models of ESP

Only single-stage wire-plate configurations will be considered in this review. This is by far the most common configuration used in commercial applications, even though there is a large number of others [5]. This includes variety of different geometries [6–8], two-stage precipitation [9], wet processes [1] or electrostatic scrubbing [10]. The new ideas developed recently try, for example, to use dielectric barrier discharge [11] or integrate particle collection with removal of gaseous pollutants [12]. The most important papers published in this area and their short characteristics are presented in Table 1.

2.1. Geometry

A few authors attempted to simulate the entire multichannel structure of ESP [23,28,51,52], but in this case a detailed discussion of processes in one channel is not possible. This can be done if only one channel, or one section of the channel, is investigated assuming that inlet velocity of gas is known. Out of two essential elements of the considered ESP, the grounded plate is pretty standard; even though it is not always perfectly flat, the details of its shape are not really critical and can be easily incorporated in any model. The most common geometry for the corona wire is a smooth cylinder. Due to its simplicity for long time it was the only shape considered; in 2D models this is practically the only choice (for example [13]). Phenomena occurring near the corona wire are the major source of computational difficulties and this forced many authors to consider just one corona electrode [13,14,17,32,41,43,45,46,48], although there were also attempts to assume a larger number: two [15,33], three [16,20,21,34,36,37,44], five [47] or more [19,30,38,39]. Surprisingly, the case of infinite number of electrodes is even simpler than the single one, because the problem becomes periodic and just one section can be analyzed with symmetry boundary conditions [18,24,27,29,42]. Helical wires have also been considered for some special supplications [53].

Even if a smooth cylinder is used as a corona electrode, application of negative voltage (used in most cases due to a better discharge stability) leads to non-uniform discharge: some number of tufts is created along the wire, which automatically adds third dimension to the model. For an ideally smooth cylinder the distance between tufts varies, controlled for example by the supply voltage. In order to have a regular set of corona injection points, the spiked corona wires can be used. They can be cylindrical [26,31,35,40] or cut from a flat tape [49,50], but more complicated shapes have also been proposed [54].

2.2. Gas flow

Predicting the gas flow in the ESP channel is probably the most computationally intensive component of the simulation. Some earlier works, which attempted to grasp the general characteristics of the problem only, were based on the assumed flow patterns, without solving the flow equations [15,18,24,27]. More complete analysis was possible using the laminar model, which was done first in 2D [13,26,31,43] then in 3D cases [33]. Electric body force was considered in majority of these papers, but sometimes this effect was considered unimportant and neglected [17,24].

It is well-known that even without corona discharge the gas flow in ESP is turbulent. However, more than 20 years ago Atten proved theoretically and experimentally that interactions between gas, ions and particles intensify the turbulence level [55,56]. It is natural that the turbulent flow model was incorporated in many models to simulate ESP; from many different options, the k-ε approach was the most popular [16,17,19–23,25,28–30,32,36–50]. The most accurate approach used so far seemed to be direct Navier–Stokes solution suggested by Soldati [34].

However, majority of these models do not include the presence of the corona wire. Often it was assumed that the size of the corona wire is so small, that it distorts the flow pattern only locally, even though this distortion can be interesting and quite complicated (swirling von Karman's vortices). These effect was investigated in the ESP geometry for the first time by Skodras et al. [39] and then by other authors [41,43,45,46,48–50].